Scintillating Bubble Chambers for Rare Event Searches

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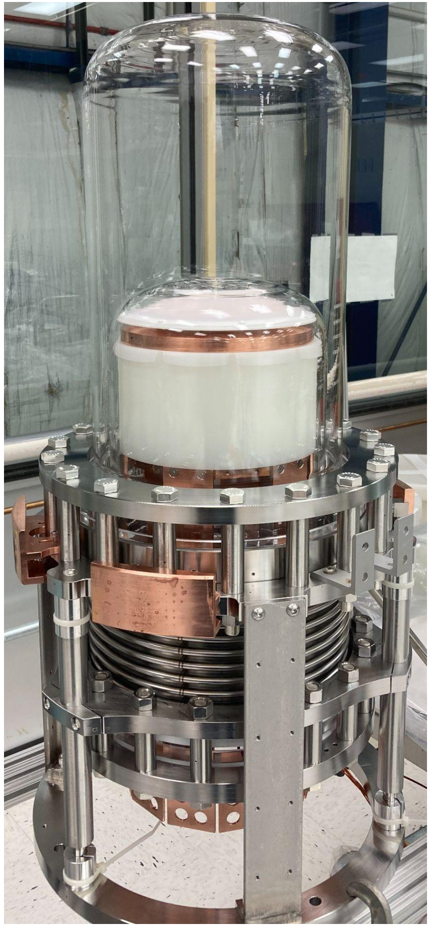
for the SBC collaboration

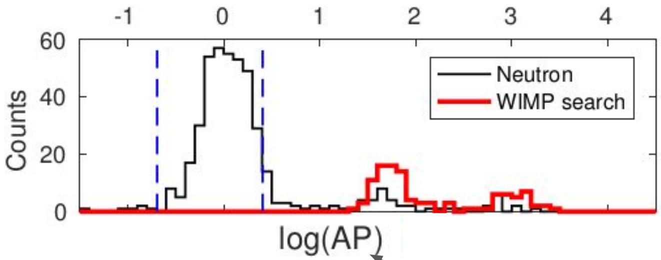
CPAD 2023

Queen's UNIVERSITY

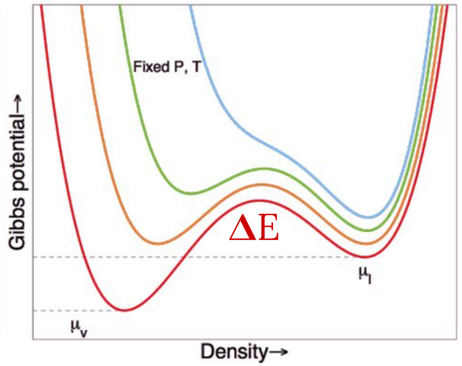


Bubble chambers

- Bubble chambers maintain target fluid in a superheated state
- High efficiency low n.r. threshold, β/γ insensitivity, n.r./α discrimination:

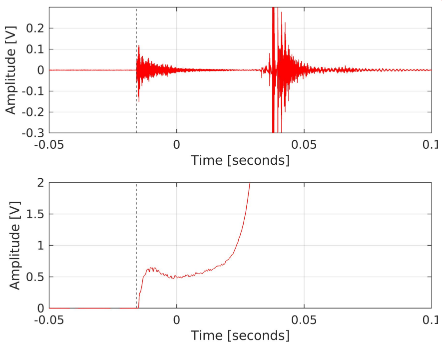


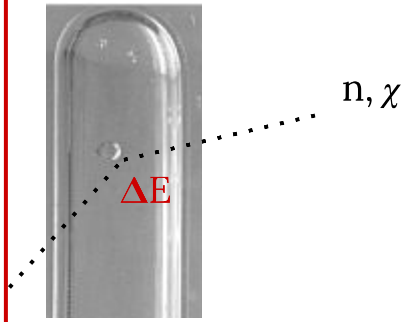
{x,y,z} + acoustics



Pressure ↓, 2 minima form

Further P ↓, Metastable superheated

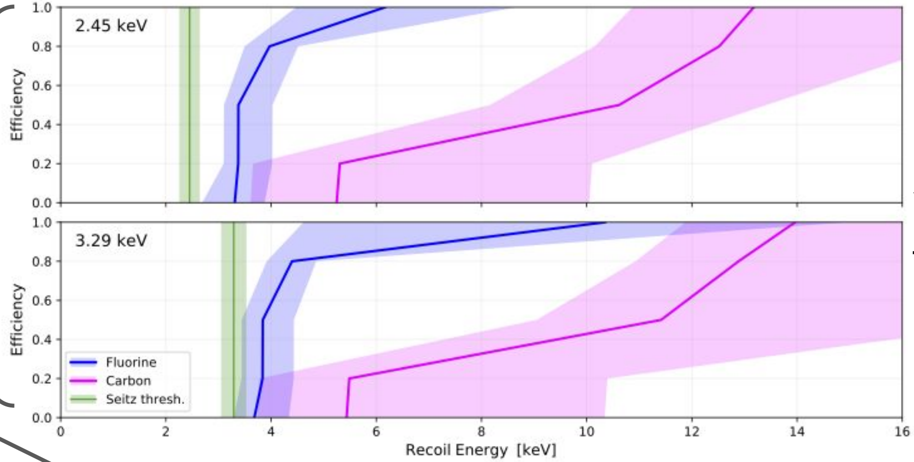




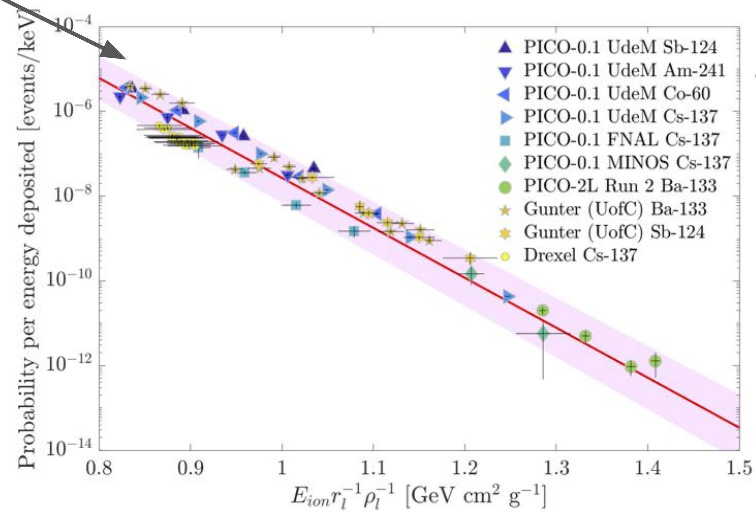
If ΔE deposited, local phase change

Bubble chambers

- Issues with freon B.C.'s
  - Threshold detectors: no energy information
  - β/γ rejection fails at low thresholds
- Liquid-noble B.C.'s
  - Scintillation provides energy information
  - Lack molecular vibrational modes to provide local heating (possible increase in β/γ suppression at low thresholds)
    - **No e.r. bubbles in pure Xe B.C., but nucleation in Xe + ethylene (quenched scintillation)**



arXiv: 2205.05771, accepted to PRD



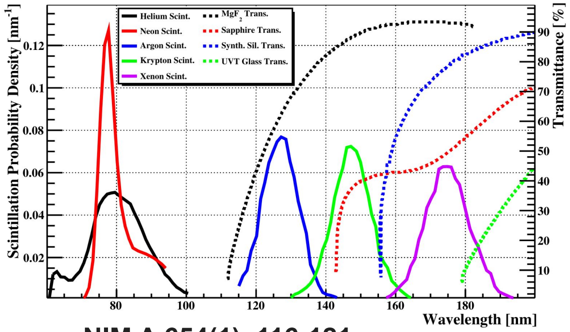
Phys. Rev. D 100, 082006

Liquid-noble bubble chambers

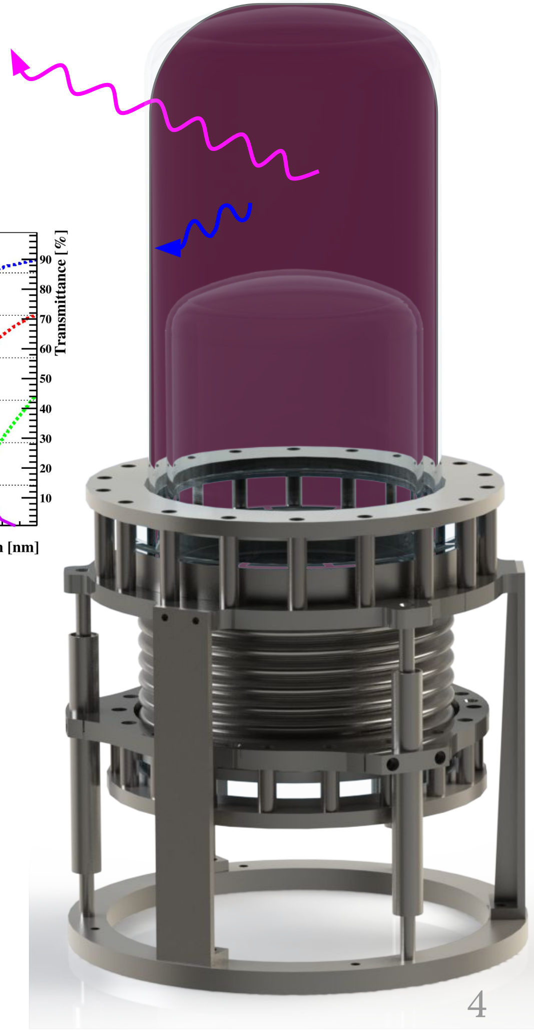
- Argon 3x lighter than Xe
  - Ar for low mass SI, Xe-doping to get the light out

- Cryogenic temperatures
  - Everything that moves, must move cold

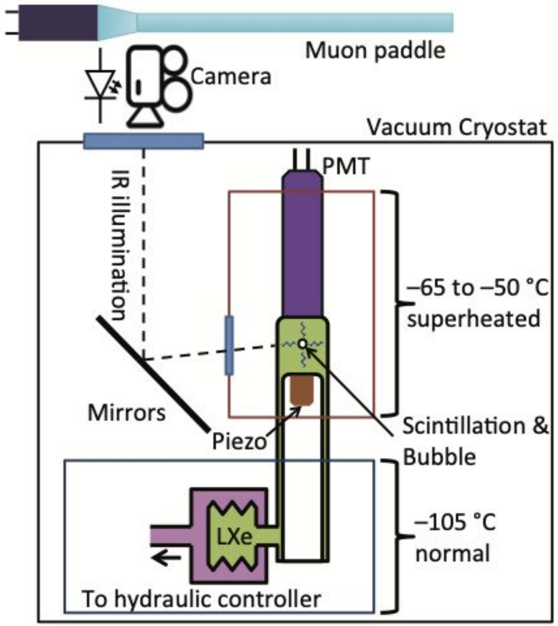
- Signal timing difference
  - Scintillation $\mathcal{O}$(ns)
  - Bubble formation/acoustic emission $\mathcal{O}$(μs)
  - Recompression $\mathcal{O}$(ms)



NIM A 654(1), 116-121.

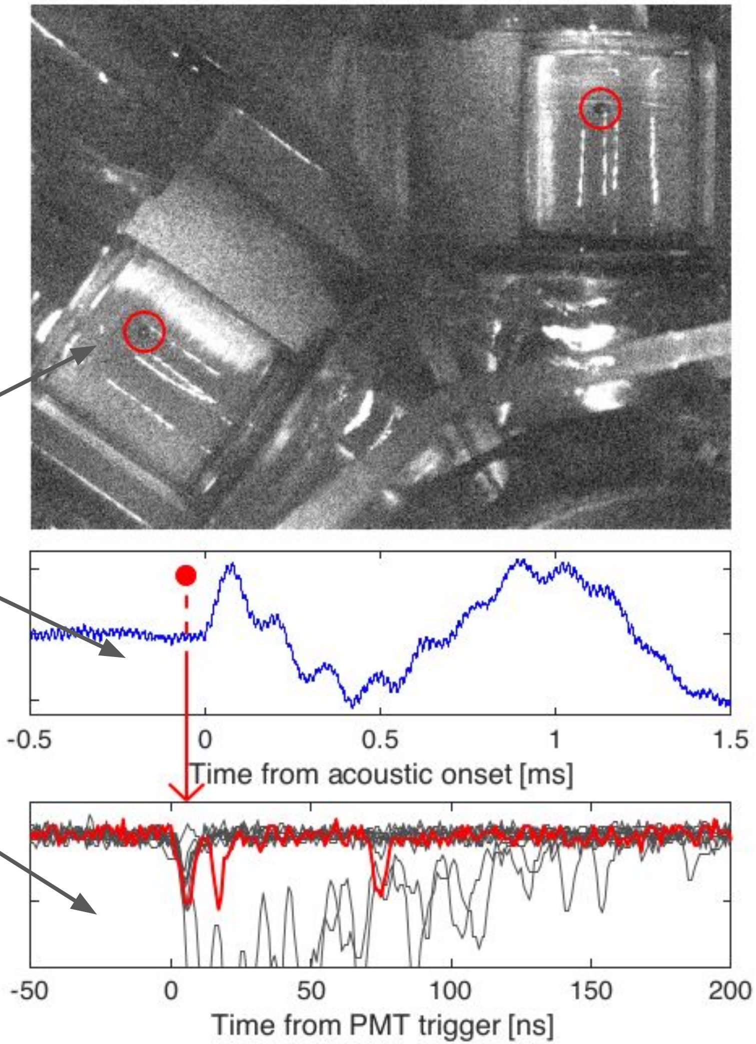


Prototype LXe bubble chamber



Simultaneous measurement of

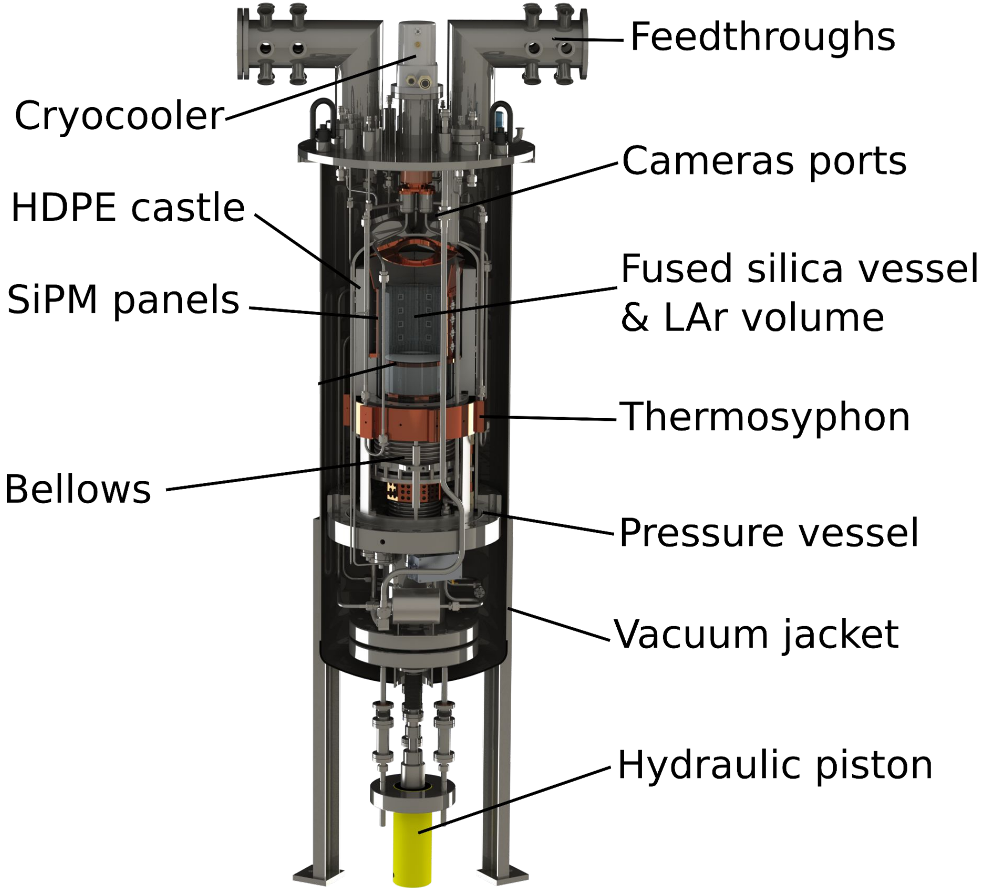
- Bubble position (cameras)
- Acoustic emission (piezo transducer)
- Scintillation (UV-grade PMT)



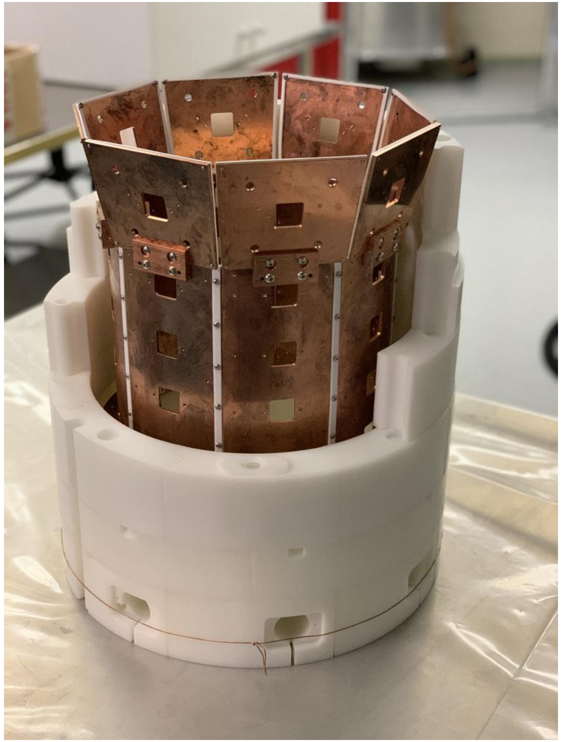
PRL 118.23 (2017) 231301

SBC detectors

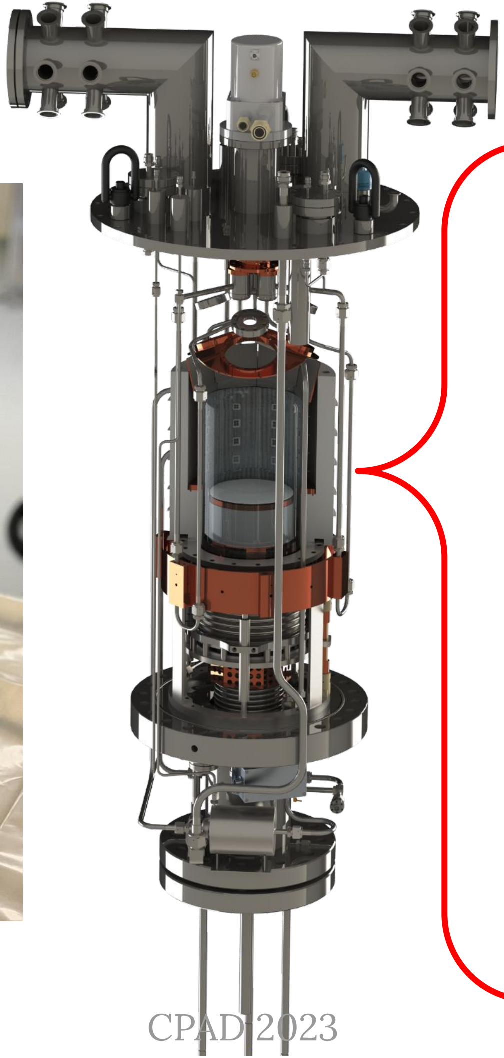
- Two functionally-identical detectors operated at:
  - Fermilab, SBC-LAr10 (engineering, calibration, CEνNS)
  - SNOLAB, SBC-SNOLAB (low bkg. dark matter)
- 10 kg LAr + Xe as a wavelength shifter targeting 100 eV n.r. threshold
- Cold region ~90 K, warm region ~130 K
- Expanded ~30 psi, compressed ~200 psi

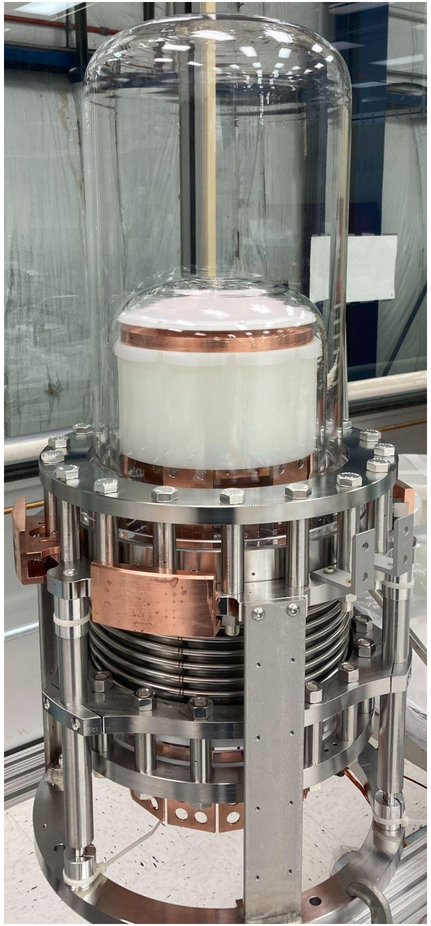


Inner vessel



HDPE castle, Cu SiPM panels

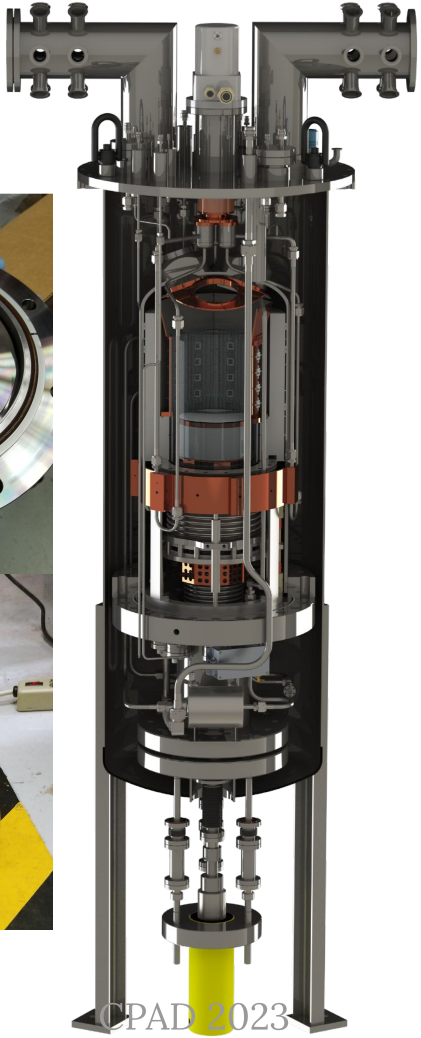




Fused silica vessels, inner tower, and bellows

Outer vessel

Cryocooler, cryogenic valves



Vacuum jacket and pressure vessel

Signal reconstruction

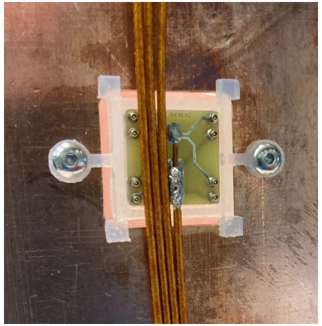
1. Bubble position:
   3 Arducam cameras

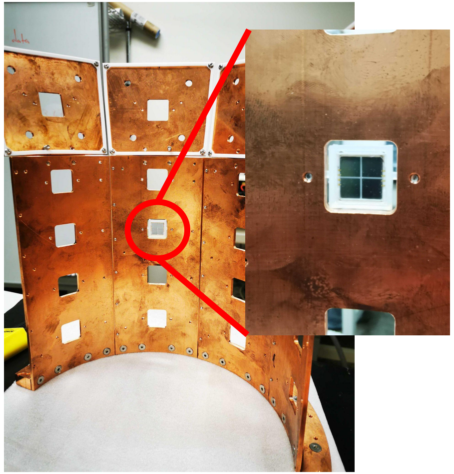
2. Acoustic signal:
   8 PZT transducers

3. Scintillation signal:
   Fermilab: Hamamatsu (20-25% QE)
   SNOLAB: FBK (25-30% QE)

SBC-LAr10 Design Goals

Target Volume	10 L (10 kg LAr @ 130 K)
Target Fluid	Xe-doped Ar, with options for pure Ar, Xe, N_2, and CF_4
Achievable Superheat	40 eV (LAr @ 1.4 bara, 130 K)
Thermodynamic Regulation	±0.5 K, ±0.1 bar (±5 eV Seitz Threshold)
Scintillation Detection	1 photon per 5 keV NR in Xe-doped Argon ($g_1 \approx 0.02$)
Bubble Imaging	100 fps, mm-resolution stereoscopic imaging
Acoustic Reconstruction	time-of-nucleation reconstructed to ±25 μs resolution
Zero-scintillation single-bubble rate (SNOLAB chamber)	1 background event per live year





Backgrounds

α-induced

Surface Po, bulk ^{222}Rn decays [purification/cleaning]

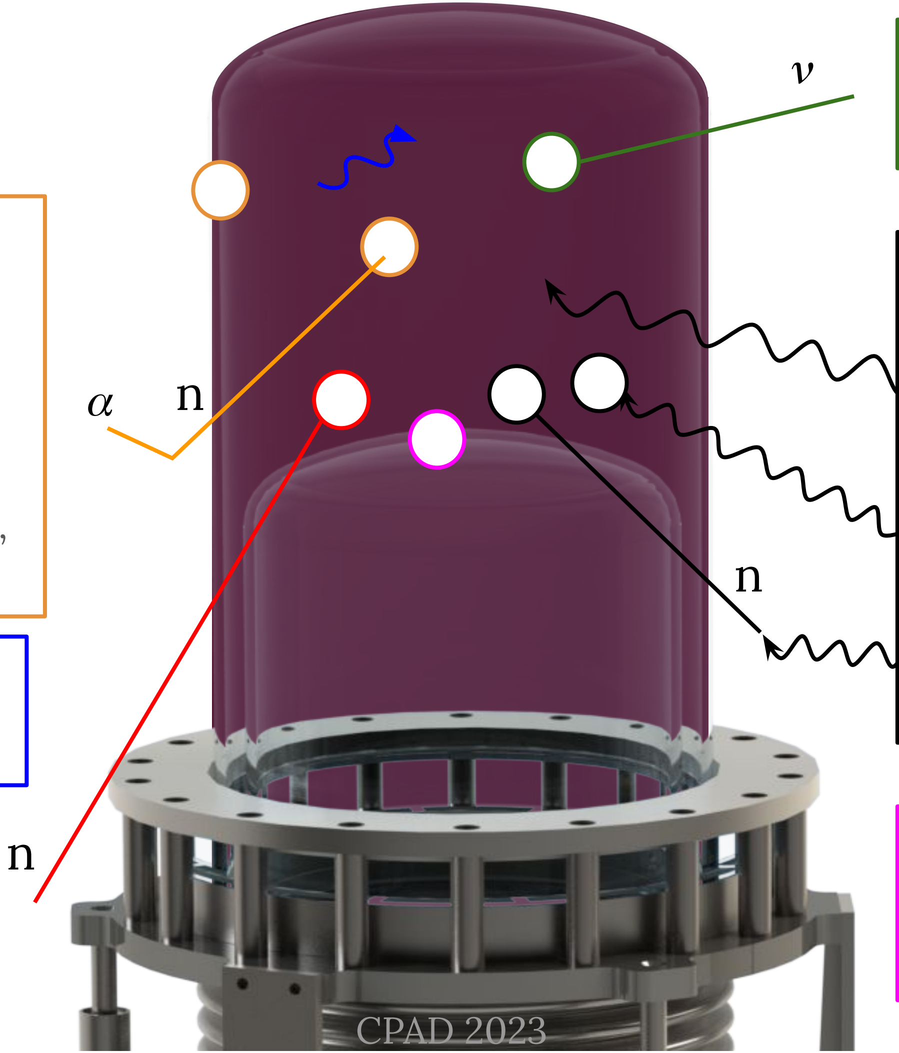
(α,n) in detector materials & LCF_4 [material selection, leaching]

β-induced

^{39}Ar [stray SiPM signals]

n-induced

Fast n [shielding/LCF_4 veto, multiple scatters]



ν-induced

^{8}B CEνNS [irreducible]

γ-induced

Compton [stray SiPM signals, material selection/shielding]

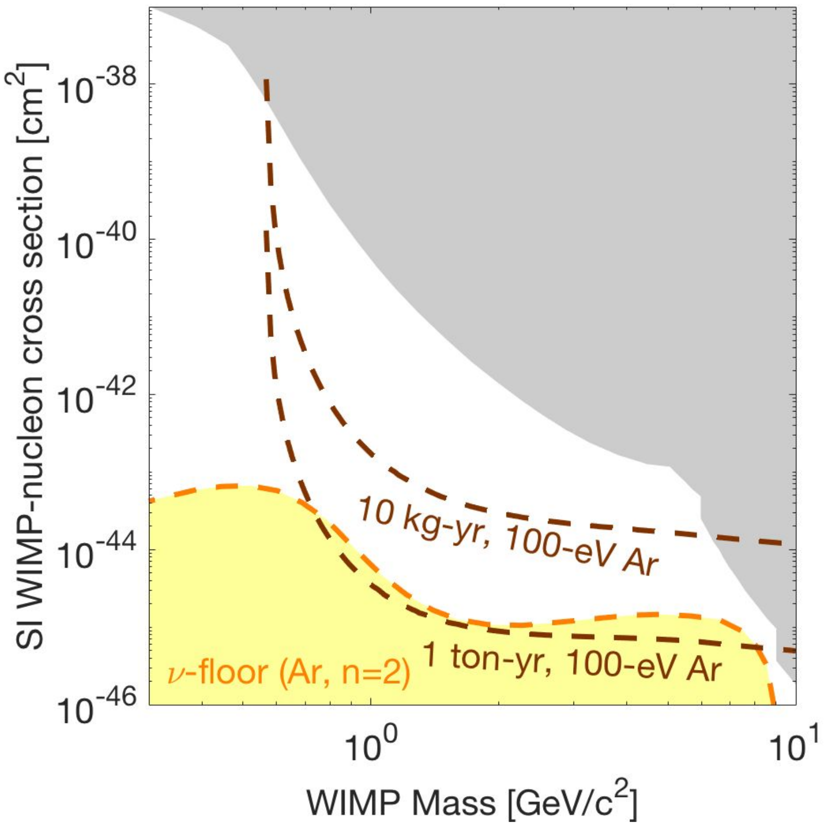
Thomson (^{40}K, ^{208}Tl) [shielding]

(γ,n) reactions in water tank [shielding]

Pathological

Surface roughness, thermal stability

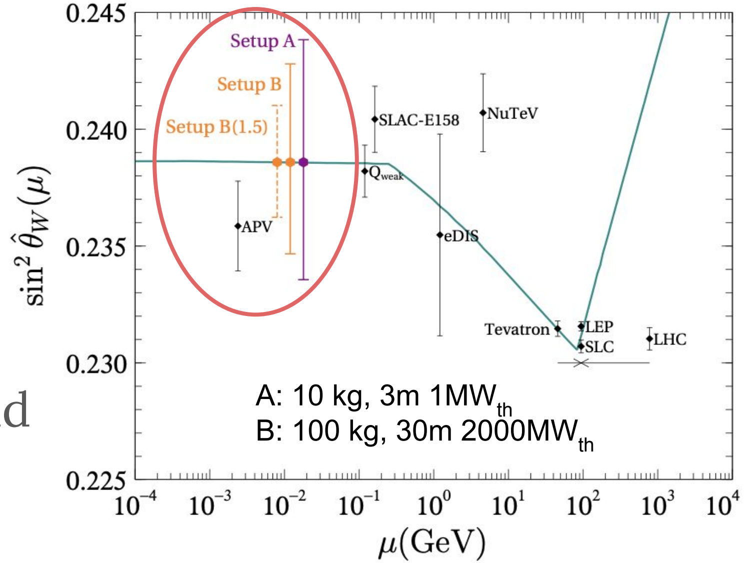
Physics potential: dark matter



- ROI: 0.1 keV - 10 keV n.r.
- SNOLAB chamber, 10 kg-year can reach 10^{-43} cm^2 @ 1 GeV/c^2
- Tonne-year can reach boundary of the Ar ν-fog
- Flexibility for other target fluids for SD searches

Physics potential: CEνNS

- MeV-scale reactor antineutrinos produce sub-keV CEνNS scattering
- Increased flux over stopped-π sources, and pure anti-ν_e signal
- Measurements of
  - Weak mixing angle:
  - Others: sterile neutrinos, unitarity violation in mixing matrix



$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F^2(Q^2)$$

$$Q_W = Z(1 - 4\sin^2\theta_W) - N$$

$F^2 \sim 1$ at low energy sensitive to Q

Check out: **PRD 103, L091301 (2021), PRD 105, 113005 (2022)**

Conclusion

- Liquid-noble chamber will probe GeV-scale dark matter and CEνNS from MeV-scale reactor antineutrinos
- Underground operation at Fermilab in early 2024
  - Final IV construction happening now
- SNOLAB TDR review early 2024
  - Space allocated, component procurement
- Check out our Snowmass white paper: **arxiv: 2207.12400** and **Universe 9 (2023) 8, 346**.
- Next talk (T. Whitis): Current status, calibration plan